Laser cooling and trapping of neutral atoms

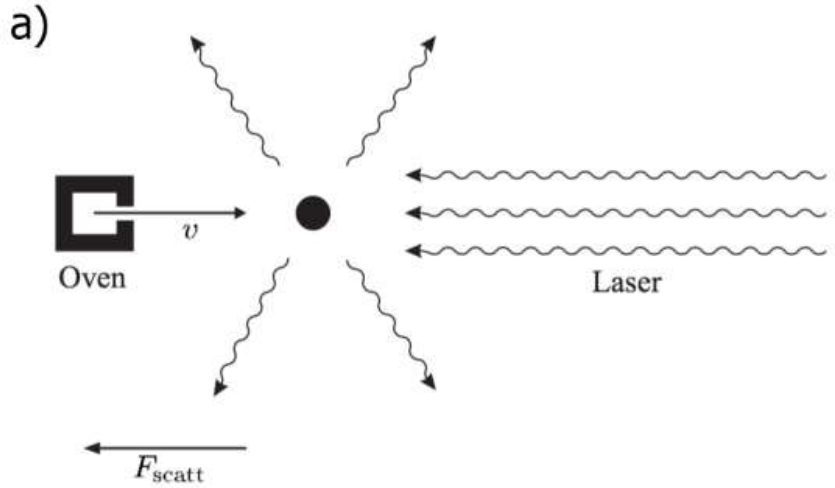
Neil Patel

Why do we cool atoms?

- Neutral atoms can be used as qubits by exploiting their internal energy levels, such as hyperfine or Rydberg states
- By using lasers and magnetic fields, these energy levels can be controlled and manipulated to perform quantum operations
- Techniques such as laser cooling and magneto-optical trapping are used to cool the atoms to near absolute zero, where their quantum behavior can be more easily controlled.

Laser Cooling - Idea

- Heat up a metal
  - Atoms are released
- Apply a laser
  - Photons are absorbed and emitted
  - Emitted in a random direction
- Scattering process
  - Force is exerted on atoms
  - atoms that are travelling toward the laser beam, slow down



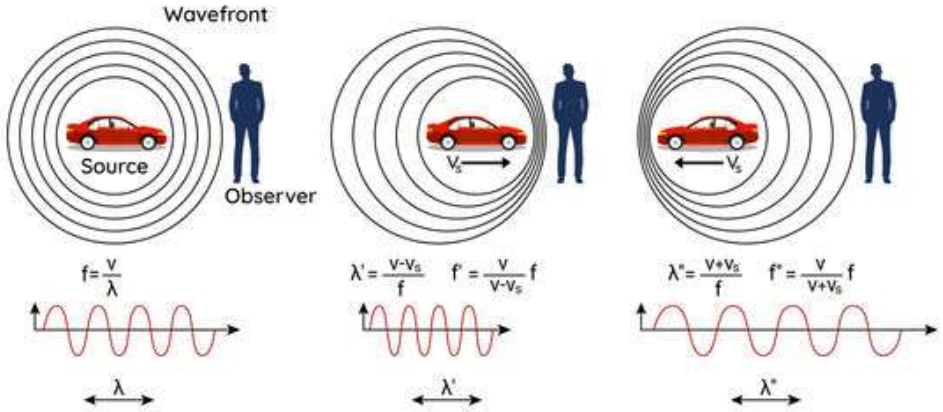
https://ultracool.ijs.si/wp-content/uploads/2020/09/LaserCoolingOfAtoms04.pdf

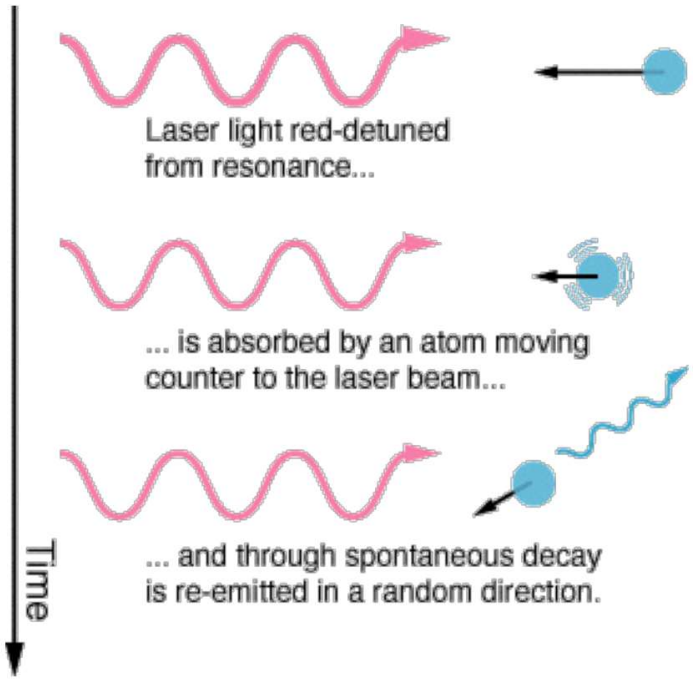
Problems?

- This will only cool atoms moving towards laser ?
- Add energy to other atoms moving other directions?
- How can this work in practice, if very precisely defined frequencies?
- The atom will experience a net change in momentum in the direction of the laser beam due to the absorption of photons
- How to create a trap for the atoms?

Laser Cooling – Doppler Effect

Ensure you only cool atoms?

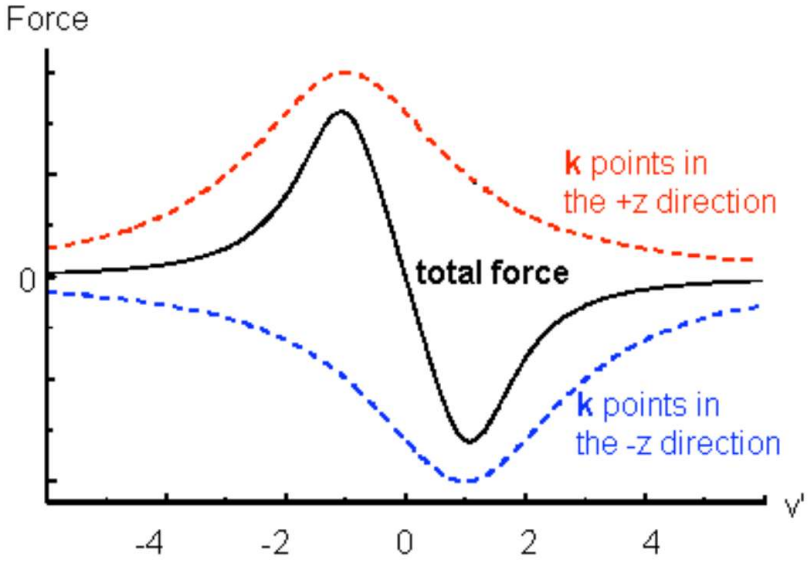


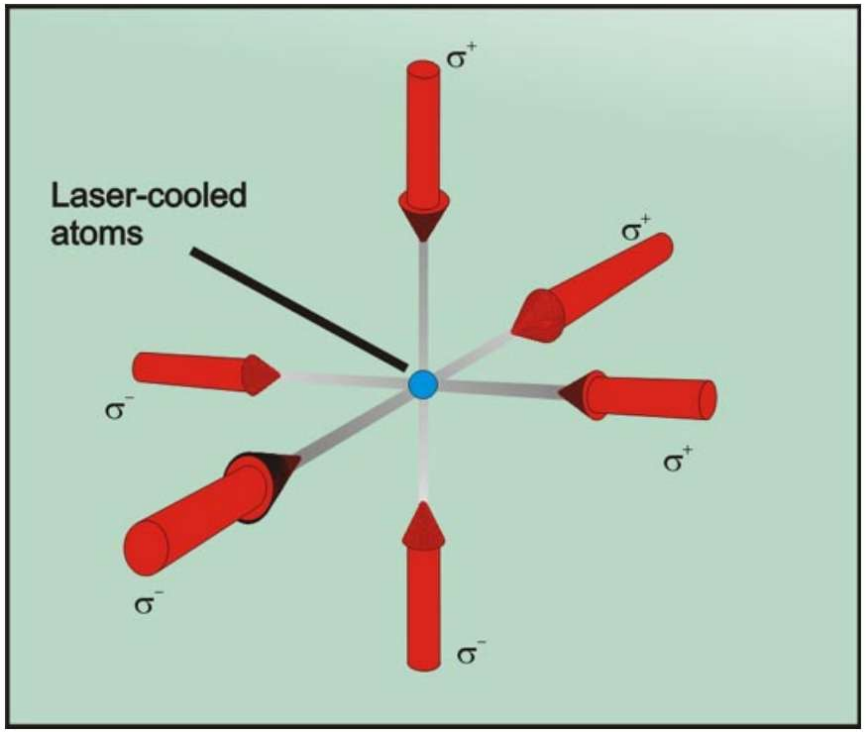


Laser Cooling - Optical molasses

What about the other directions? How to slow?

- Add more lasers
  - Creating an damping
  - Name molasses comes from

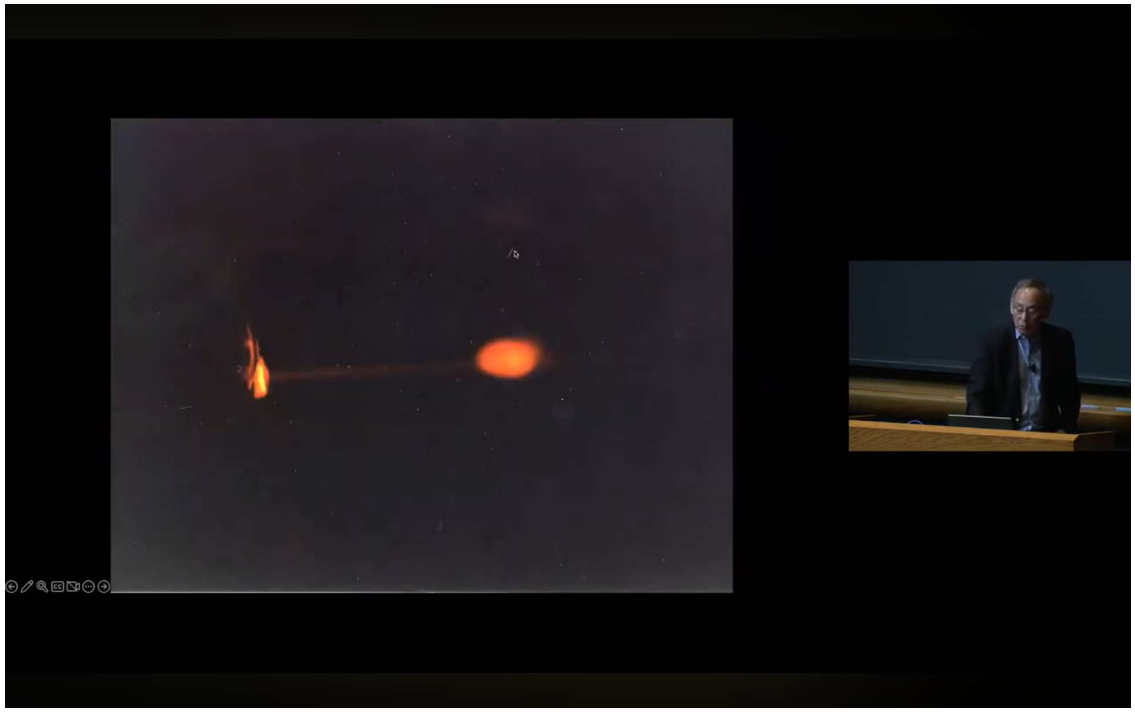




https://web.stanford.edu/~rpam/dropoff/Phys041N/lecture6-lasercooling.pdf

Laser Cooling - Optical molasses

- few hundred microKelvin (μK)
- Additional cooling methods



CHU, Steven

Trapping Atoms (MOT)

- Zeeman Splitting
  - Shift energy levels
- Scattering force proportional intensity
  - now is related to location

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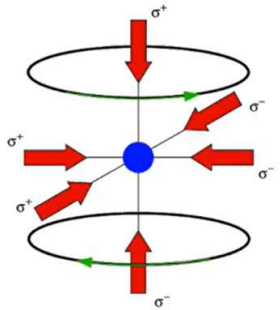
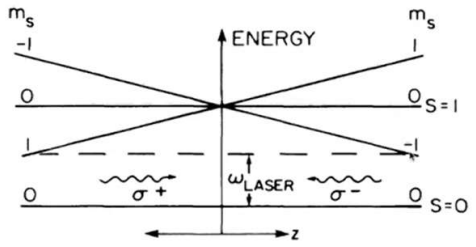
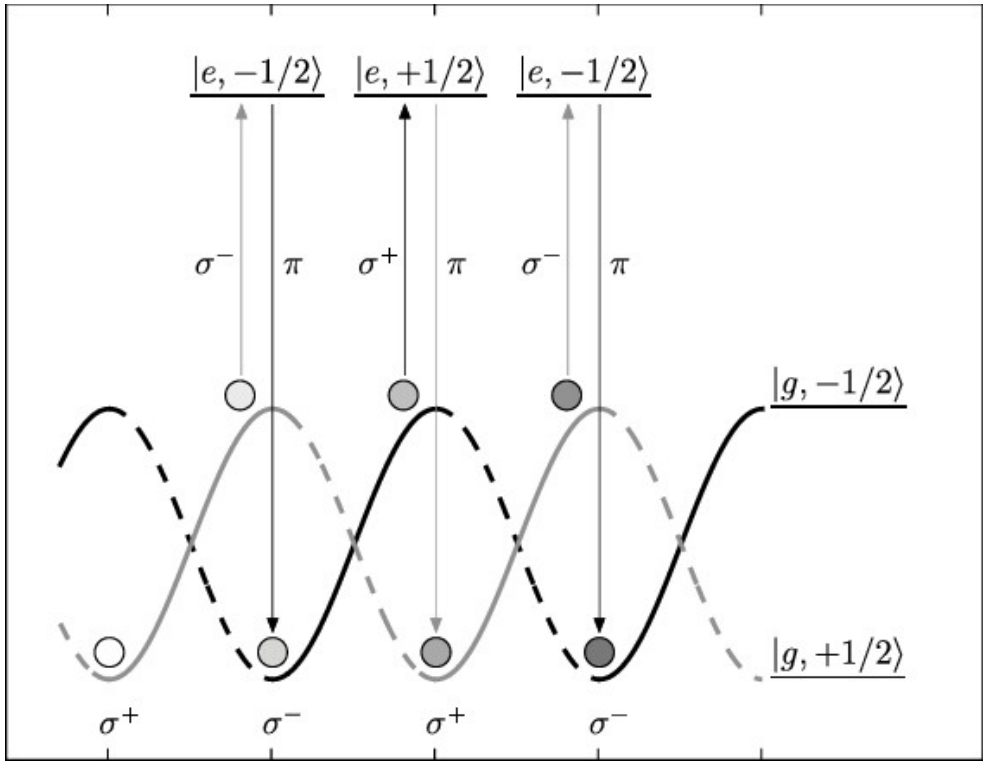
Trapping of Neutral Sodium Atoms with Radiation Pressure

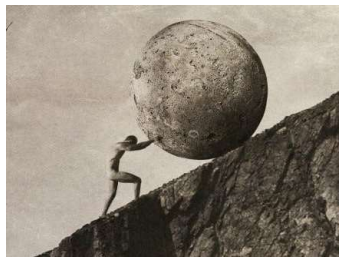
E. L. Raab,[a] M. Prentiss, Alex Cable, Steven Chu,[b] and D. E. Pritchard[a]
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 16 July 1987)





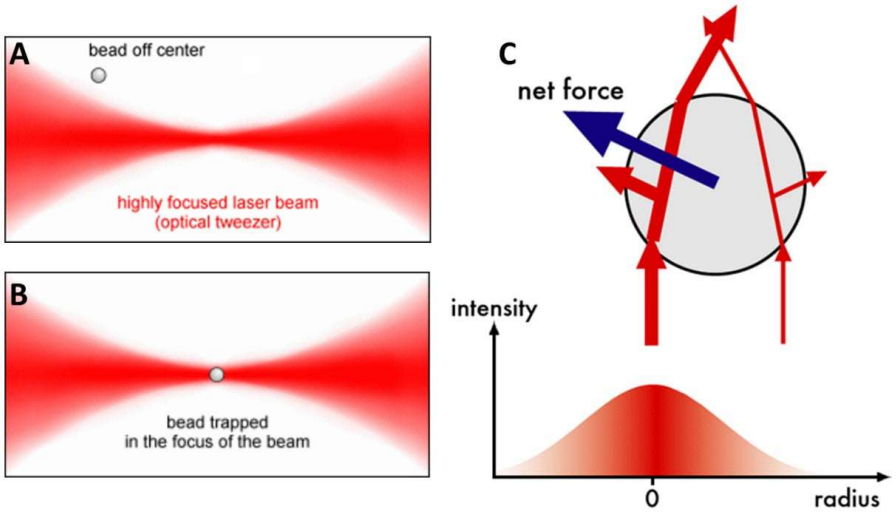
Sub-Doppler Cooling (Sisyphus Cooling)

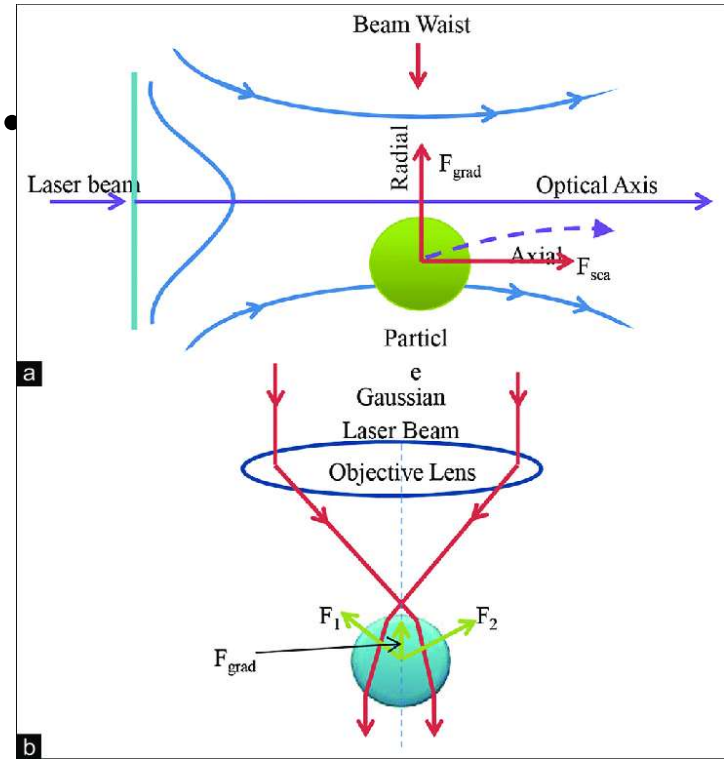




Symmetry and Transport in Cold Atom Ratchets - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/llustration-of-the-principle-of-Sisyphus-cooling-for-an-atom-with-Jg-1-2-Je-3-2-in_fig7_304265014 [accessed 12 Dec 2025]

Trapping of Atoms

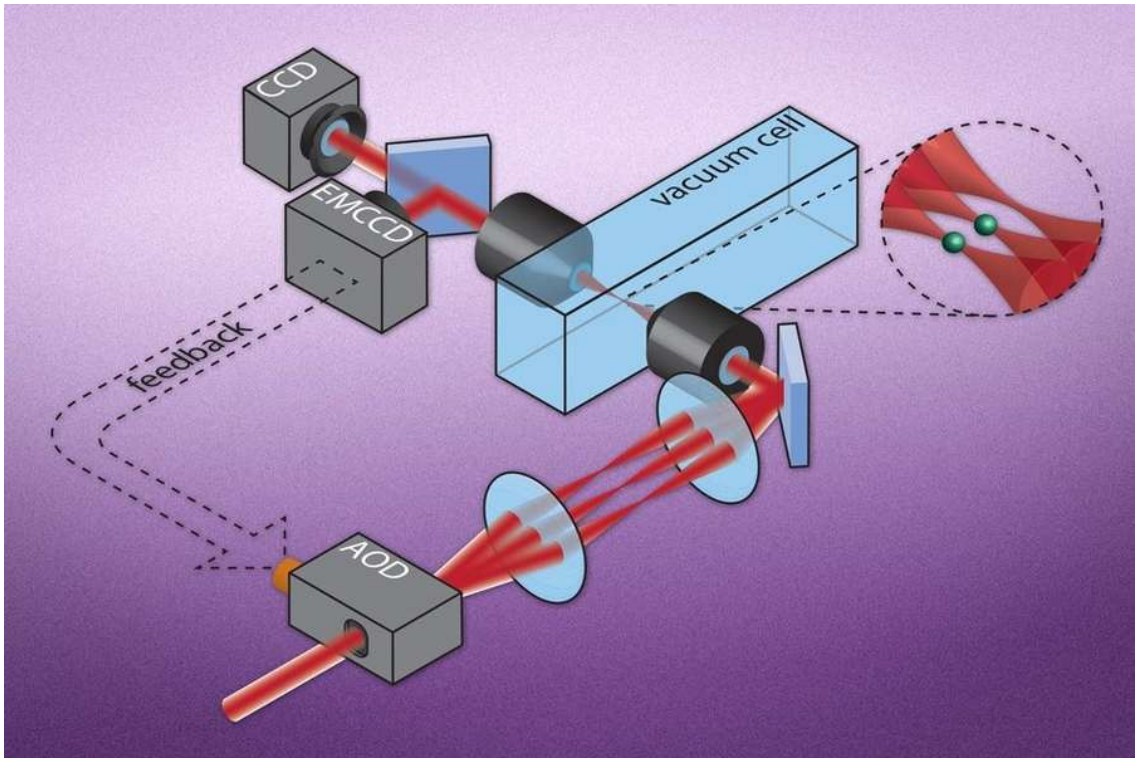




https://www.teledynevisionsolutions.com/learn/learning-center/scientific-imaging/optical-trapping/

Trapping of Atoms

- Trap atoms
  - One or none in trap
  - stochastically fill array
  - High intensity of laser
  - Controlled with radio frequencies
- AOD
  - Move laser depending on w
  - Has bandwidth (50 atoms)



Endres, Manuel, Hannes Bernien, Alexander Keesling, Harry Levine, Eric R. Anschuetz, Alexandre Krajenbrink, Crystal Senko, Vladan Vuletic, Markus Greiner, and Mikhail D. Lukin. “Atom-by-Atom Assembly of Defect-Free One-Dimensional Cold Atom Arrays.” Science (November 3, 2016).

Sideband Cooling (beyond MOT and for ions)

- 200nk

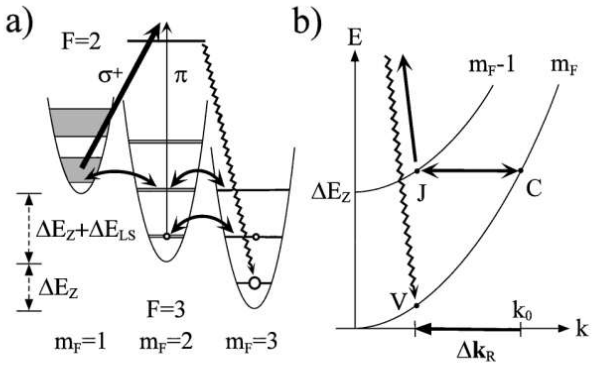
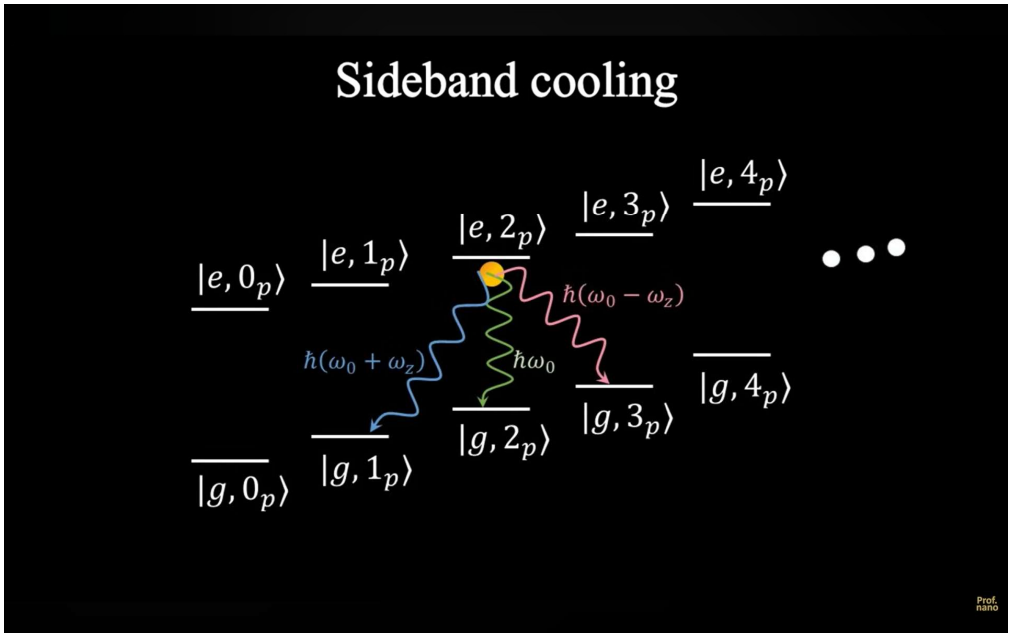


FIG. 1. (a) Vibrationally excited atoms are cooled quickly by degenerate Raman transitions (double-sided arrows) and fast σ^+ optical pumping, while the final cooling stage uses only weak π pumping. This scheme strongly suppresses reabsorption heating. (b) Initially unbound atoms are transferred from $m_F(C)$ to $m_F - 1(J)$ when a two-photon degenerate Raman transition satisfies energy and momentum conservation. Optical pumping back to $m_F(V)$ cools the atoms by one Zeeman energy splitting ΔE_Z.

440



https://www.youtube.com/watch?v=5qpXdGSLWig

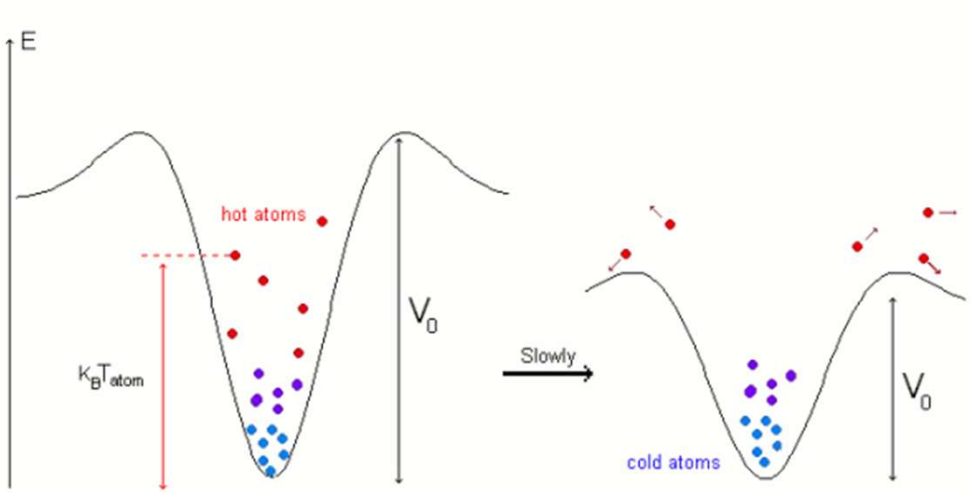
Beyond Optical Molasses: 3D Raman Sideband Cooling of Atomic Cesium to High Phase-Space Density Andrew J. Kerman, Vladan Vuletic´, Cheng Chin, and Steven Chu Department of Physics, Stanford University, Stanford, California 94305-4060

Refrences

- https://ultracool.ijs.si/wp-content/uploads/2020/09/LaserCoolingOfAtoms04.pdf
- https://www.youtube.com/watch?v=4J88tD7V9MU
- https://web.stanford.edu/~rpam/dropoff/Phys041N/lecture6-lasercooling.pdf

Evaporative Cooling

- Have a trap
  - N * KT = minim energy to leak out
  - Lower n (trap parameter)
  - Overtime shrink distribution



https://ocw.mit.edu/courses/8-422-atomic-and-optical-physics-ii-spring-2013/resources/lecture-18-techniques-for-ultralow-temperatures/

http://large.stanford.edu/courses/2009/ph376/amet1/